DETERMINING SERIES ARCING IN 115 VOLT, 400 Hz, AND 28 Vdc SYSTEMS

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Objective

This paper describes the electrical series arc tests conducted by the Federal Aviation Administration (FAA) and the Naval Air System Command (NAVAIR). The objective is to determine how to test a single wire and terminal lug to prevent damage from series arcing caused by aircraft vibration at approximately 3, 6, and 9-amps for 28 Vdc, and 115 Vac 400 Hz single phase. The results include system voltage, load current, arc voltage, and lug temperature.

Background

To create a realistic approach to identifying series arcing density and the resulting temperature rise, an incident from past service difficulty reports was recreated. After reviewing 5 years of Service Difficulty Reports, the main series arcing incidents (the majority that could be identified) came from loose terminals in window heat, lighting, and on circuit breakers. Evidence of these events was characterized by smoke generation and discolored or melted terminals. The circuit protection used in these incidents did not always recognize the fault and, therefore, did not trip the circuit before the wire or terminal smoking temperatures were exceeded.

In a series arcing event, an intermittent high-temperature arc conducts for a short period of time. The arcing causes carbon to build up in the connection, which restricts the conductive area of current flow. As the event continues, the connection increases in resistance and continues to drop more and more voltage across the connection. This causes the heat in the connection to rise, due to the insulating properties of the material being generated. This material insulates electrically and thermally. This restricts the amount of heat to the bimetallic element in the circuit protection, causing the temperature in the wire to exceed its limits.

To replicate a series arcing event on a circuit breaker, the terminal on the load side of the breaker was loosened. This particular setup was chosen because most of the variables could be controlled and repeated with a standard setup. The loosened terminal circuit breaker test had no additional electronics between the circuit protection and the load. As an example, window heat usually has a controller between the circuit breaker and the elements on the window, most of the series events on lighting are on florescent tubes, which have lighting ballast between the lighting load and the circuit protection. With all these restrictions to consider, the loose terminal on the circuit breaker seemed to be the simplest circuit to be reproduced in the laboratory and would also reduce variables and sources of errors.

A loosened terminal lug will vibrate according to the aircraft vibration. The aircraft vibration ranges from 20-2000 Hz with fixed harmonics based upon the type of aircraft. The vibration with the highest energy and maximum displacement falls in the 20-100 Hz range for propeller planes and helicopters. Fixed-wing aircraft have the highest energy in the higher frequencies (2000 Hz), but the displacement is lower. Series arcing can only occur when the loose terminal lug has enough displacement to make, and break, contact with the screw. The best chance for producing arcing in a laboratory environment (vibration table) would be when implementing lower frequency bands of the random profile.

This paper's intent is not to discuss loose connection heat damage due to a high-impedance connection (glowing plug) from generation of copper oxide fretting. This type of effect occurs when a loose terminal lug and the connection become dirty from corrosive effects, restricting electrical current and heat flow. While carbon buildup is a part of the arcing process on a loose terminal, a contaminated connection would have a very different current signature. This paper will discuss the potential for testing series arcing that causes heat or arcing damage on circuit breaker load terminal connections.

Test Setup

A standard 10-amp MS3320 circuit breaker was mounted to a programmable vibration table, and the temperature measured by crimping a thermocouple to the load side of the terminal lug (as shown in figure 1). A single #18-gauge wire with a #8 lug was prepared with a thermocouple on top of the #8 lug. The lug was tightened-down with a screw and backed off one full turn. The thermal circuit breaker was rigidly mounted to reduce the influence of the mounting panel.

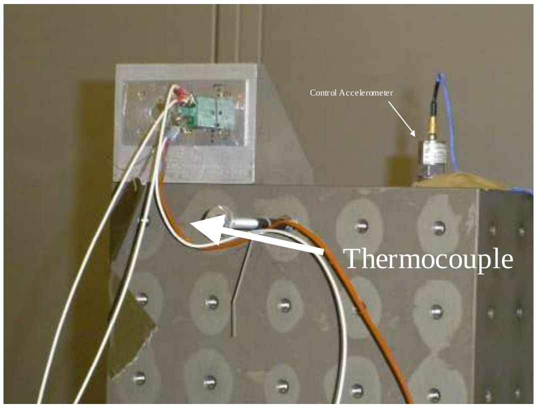

Figure 1. Temperature measured on the arcing load terminal with thermocouple.

A P-3 propeller aircraft vibration profile was chosen at a maximum of 87 Hz. This frequency was fundamental to provide the most energy to displace the terminal lug and to provide the highest frequency of arc density. An accelerometer was attached to the mounting surface to monitor the vibration profile. The vibration profile and subsequent responses are shown in Figure 2.

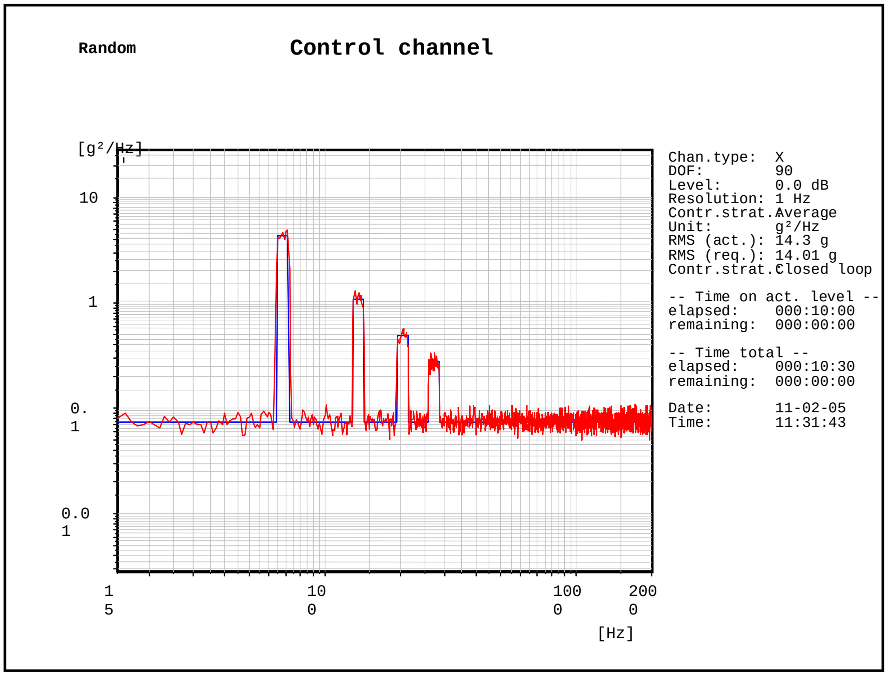

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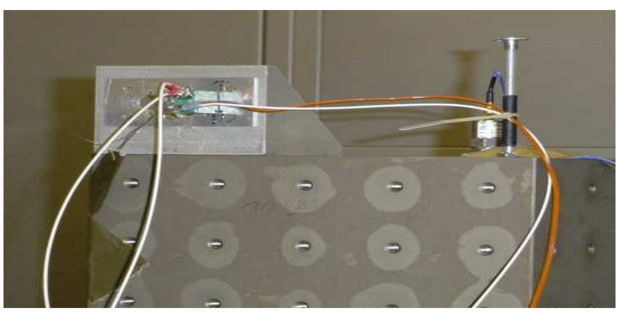
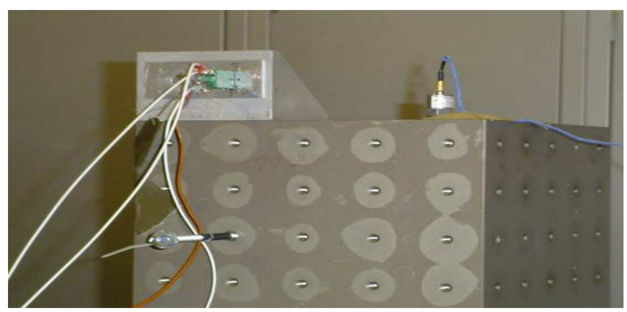
Figure 2. Vibration response.

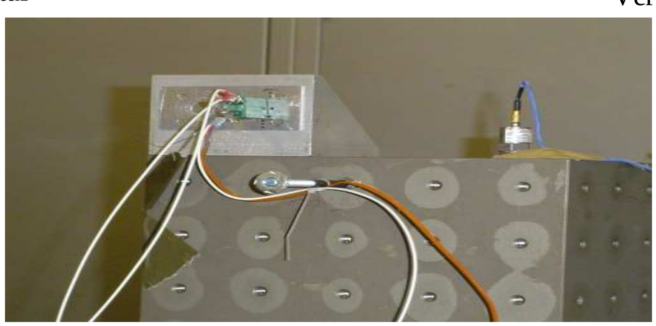
The system voltage, phase current, and the arc voltage were recorded for all tests with a Nicolet Vision Scope at 100 kilo samples per second. The lug temperature was measured by the scope for the tests 15-25 at 10 samples per second. Figure 3 shows a vertical, horizontal, and bent wire installations used in the tests.



Horizontal



Vertical



Bent

Figure 3. Wire Installations.

Approach
These tests were setup in two groups. The first test series determined the way the tests should be performed to gain the maximum temperature rise using a single wire, lug on a screw terminal and the position of the wire (vertical, horizontal, bent). The second test series was designed to measure the temperature, arc density, arc energy, and circuit breaker response to the temperature rise caused by the series arcing.

Results
The results of arcing density and arc energy with a wire in different positions are show in Table 1.

Table 1. Defining series arc density on a single-phase MS3320 with different wire positions

Test No.	Current (Amps)	Frequency (Hz)	BKR Tripped (Yes/No)	Arc (start) (Arc/sec)	Arc (end) (Arcs/sec)	Wire position Horizontal/vertical/bent)	Trip Time (min:sec)
2	2.7	400	No	91	41	Horizontal	N/A*
7	2.7	dc	No	51	111	Horizontal	N/A*
3	6.8	400	No	180	407	Horizontal	N/A*
8	6.8	dc	No	118	290	Horizontal	N/A*
4	8.7	400	Yes	398	368	Horizontal	0:52
5	8.7	400	Yes	340	887	Vertical	1:09
9	8.7	dc	Yes	208	488	Horizontal	0:19
11	8.7	dc	Yes	1330	412	Vertical	0:31
6	8.7	400	No	52	8	Bent	N/A*
12	8.7	dc	No	124	298	Bent	N/A*
10**	8.7	dc	No	124	318	Horizontal	N/A*
13**	8.7	400	No	116	259	Horizontal	N/A*

* Did not trip in 10 minutes operation   ** cleaned terminals

The data also reveals that arcing density on Vdc is somewhat greater than on VAC (compare Figures 4 and 5). No visible distortion was seen in the ac voltage and current time domain waveforms when the arc voltage was less than 40 Vac peak (measured at 100,000 samples per second). Figure 4 shows the voltage, current, and arc voltage (voltage across the circuit breaker and load terminal lug) during test 4, represented in yellow, red and green waveforms respectively.

Figure 4. AC 400 Hz 20 ms/div Time Scale Zoomed to 10 ms/div Varc Vertical Scale 20 V/div.

When using a 28 Vdc potential, the current waveform became distorted when the arc voltage reached 5 volts, Figure 5. The dc series arcing was also shorter in duration for a particular event.

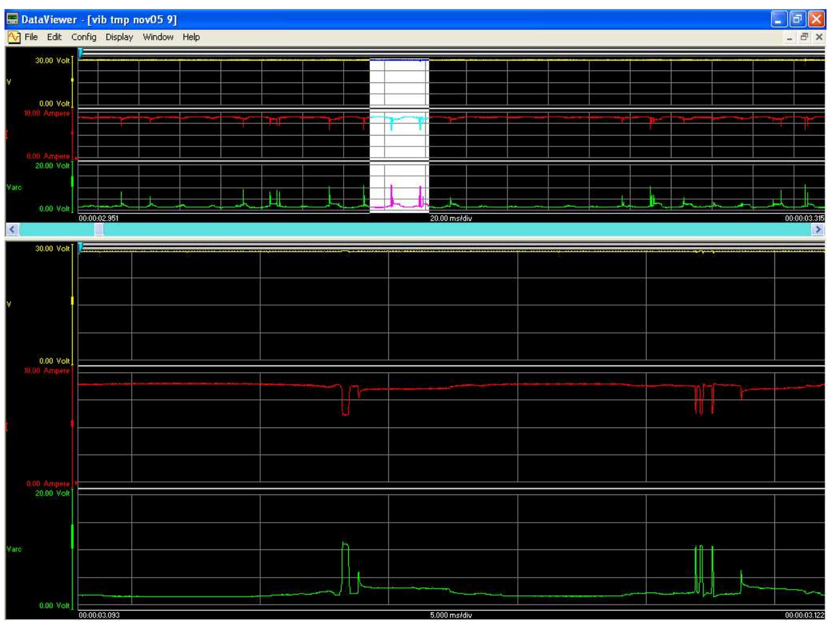


Figure 5. 28-Vdc 20 ms/div Time scale Zoomed to 5 ms/div Varc Vertical Scale 5 V/div

Table 1 shows that for tests 4, 5, 9, and 11 with a fixed vertical or horizontal wire, the series arcing of 8.7 amps heated up the terminal enough to trip the thermal circuit breaker. The series arc of less than 6.8 amps did not trip the thermal circuit breaker as seen in tests 2, 7, 3, and 8. For bent wires, conditions in the lower arc density did not create enough heat to trip the thermal circuit breaker even at 8.7 amps, as seen in tests 6 and 12, however, the number of arcs per second increased with current. Series arcing density for 2.7 and 6.8 amps ranged from 200-400 arcs per second. The series arc density ranged from 200-1330 arcs per second for 8.7 amps. In tests 10 and 13 (terminals cleaned and operated at 8.7 amps), the thermal circuit breaker did not trip during the 10-minute window, due to a lower arc density than in tests 4, 5, 9, and 11.

The second series of tests showed the arcing density and the temperature rise along each of the series arcing tests, starting at 25°C. The maximum temperature for the wire lug terminal operating at 2.7 amps reached 57°C, for 6.8 amps it reached 119°C, and for 8.7 amps it reached 127°C. For tests 18, 21, 17, and 20, arc density did not exceed 400 arcs per second as shown in table 2. Only tests 16 and 18 tripped the thermal circuit breaker. The temperature rises for the three current ranges are shown in Figures 6 (3 amps), 7 (6.5 amps), and 8 (8.4 amps). The temperature rise shown in Figure 6 steadied out at about 7.5 minutes. Figure 7 shows the temperature steadied out at 8.75 minutes. Figure 8 shows the temperature never leveled off.

Table 2. Defining series arc density on MS3320 with terminal lug temperatures.

Test #	Current (Amps)	Frequency (Hertz)	BKR Tripped (Yes/No)	Arc (start) (Arc/sec)	Arc (end) (Arcs/sec)	Max temperature (C)	Trip Time (min:sec)	Temp Rate C/min
18	2.7	DC	No	82	62	45	N/A*	3.2
21	2.7	400	No	44	258	57	N/A*	13
17	6.8	DC	No	106	168	107	N/A*	17
20	6.8	400	No	189	377	119	N/A*	8.2
16	8.7	DC	Yes	807	2193	127	0:34	5.4
19	8.7	400	Yes	293	565	104	4:16	8.3

* Did not trip during the 10 minutes operation

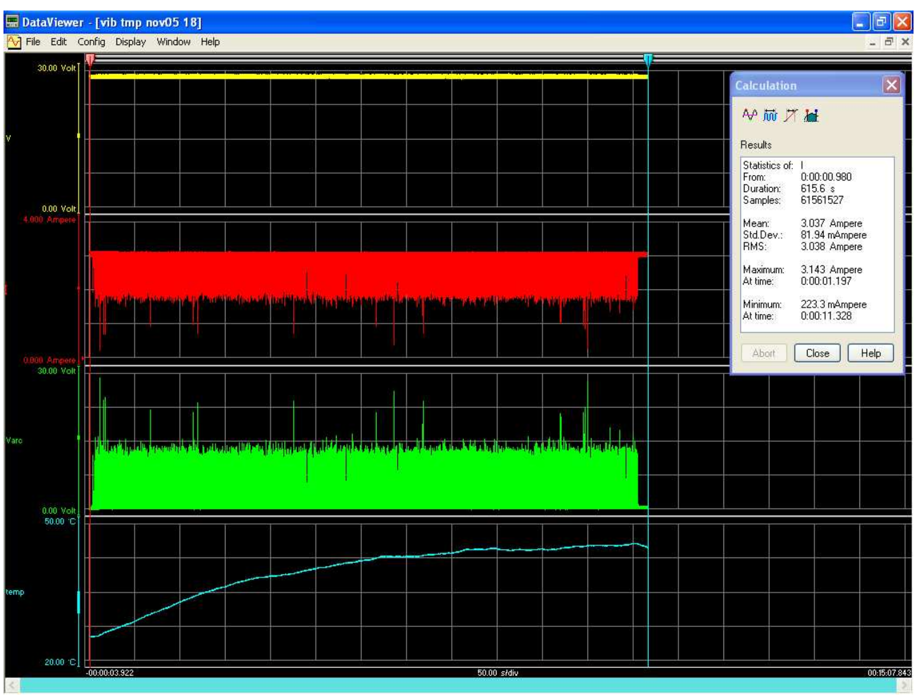


Figure 6. Temperature rise for 3-amps.

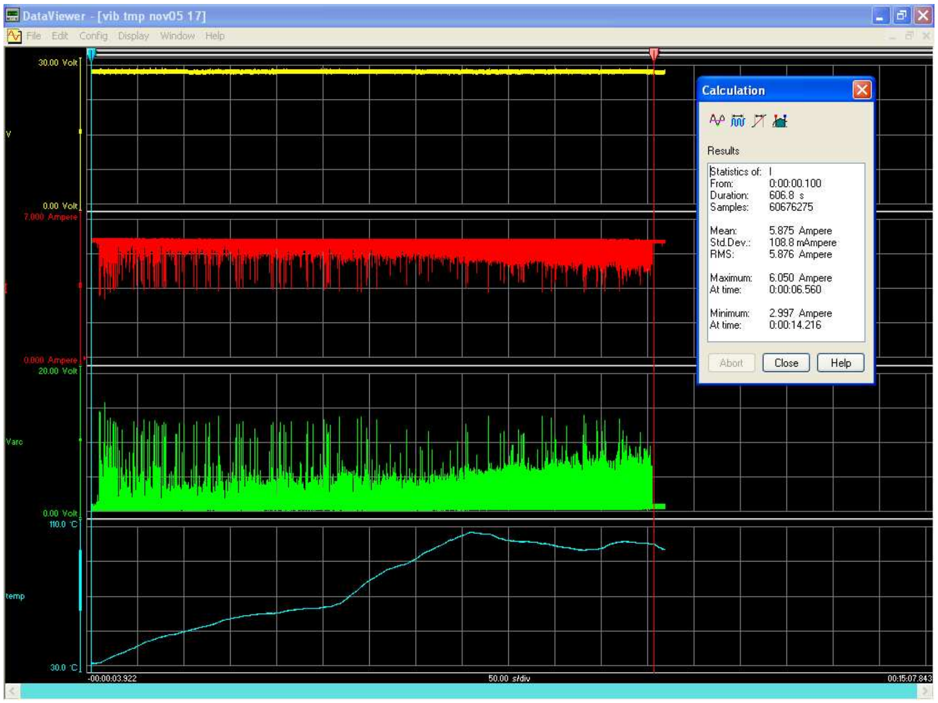


Figure 7. Temperature rise for 6-amps.

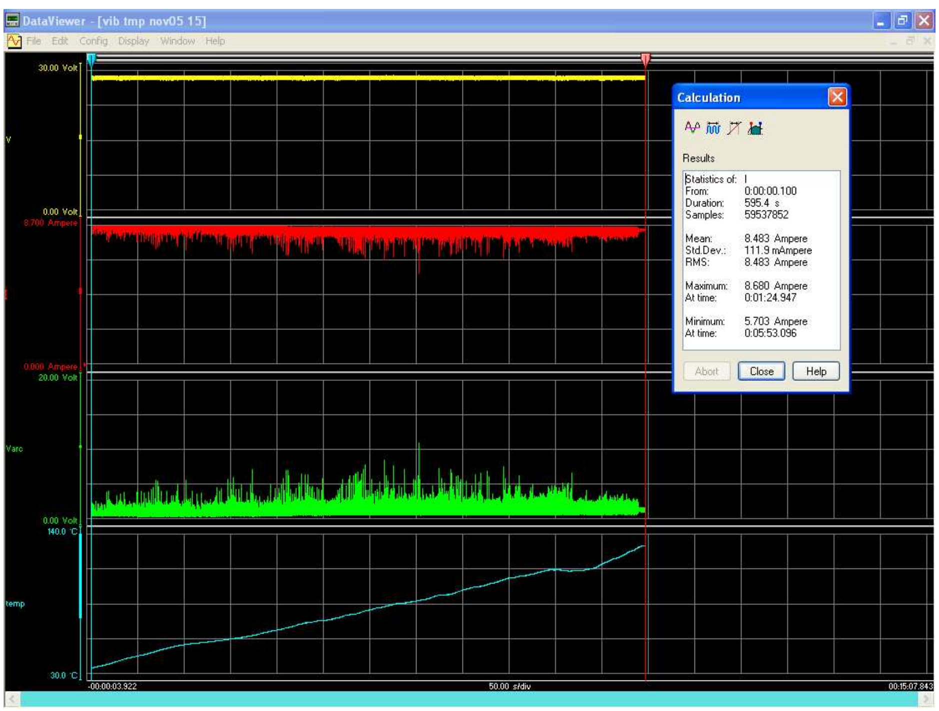


Figure 8. Temperature Rise for 8.5-amps.

Discussion

Defining what a series arc is and when it does damage to the wire is a multi variable task. The variables that can cause a series arcing on a loose terminal lug are aircraft vibration, wire installation, and carbon build up. These three variables result in series arcing over time, causing temperature increases above what the terminal lug is designed to withstand.

Aircraft Vibration

Loose terminal lugs cause high impedance conditions and arcing related to vibration. Loose terminal lug on circuit breakers happen when vibration causes a screw to loosen. The tester tightened the screw on the circuit breaker terminal, and then backed the screw off one turn. The maximum distance for a series arc on a #8 screw and lug is 0.1 inch. Arcing, due to vibration, is a function of frequency and displacement; the lower the frequency the higher the displacement. Thus, a frequency range between 20-100 Hz will provide the most displacement. Aircraft vibration frequency specifications follow DO-160 and MIL-STD-810. This test used the turboprop vibration profile for P-3 Orion aircraft from MIL-STD-810. The selected profile provided the best environment for arcing due to the combination of displacement and frequency. The arc density achieved in these tests would be a worst-case scenario for arc density due to continuous vibration.

Wire Installation

Aircraft circuit breakers are installed in panels to allow easy access by operators or maintenance personnel. The wires connecting the circuit breakers to the loads are installed according to wire installation specifications MIL-W-5088 and MIL-STD-7080. The wire installations vary from aircraft to aircraft. A typical installation will vertically mount the circuit breaker with terminals on the top and bottom. The wire coming out of the load terminal will typically be oriented vertically and connected to a wire bundle; however, horizontally oriented wires are permitted. The wire can also have a strain-relief bend to reduce mechanical stress. As tests showed, a taunt wire created conditions to increase the number of arcs; however these arcs provided little distortion in the current waveform. A loose wire (bent condition) caused more distortion in the current waveform, but did not have as big temperature rise. A wire with proper strain relief will increase the arc density, which will increase temperature rise if the wire is not biased against the screw.

Clean Versus Carbonized Terminals

An electrical arc causes plasma, which is hot enough to melt and carbonize metal (6000°C -1000°C). The more carbon build up that occurs, the more heat that is transferred to the metal. Series arcing is a string of events that carbonize the metal over tens of minutes to hours. The circuit breaker terminal's physical condition plays a key role in heating up the terminals. When a terminal becomes dirty, there is less metal to conduct the current and heat. As the surface area becomes contaminated, localized heating occurs. A test was preformed with a clean terminal lug, using a #2 pencil with the lead from the pencil in the inside of the lug. The testing indicated that clean terminals, drawing 8.7 amps, did not heat up enough to trip the circuit breaker. However, after continuing for 10 minutes with the lug contaminated with pencil lead, at 8.7 amps, enough heat was generated to trip the circuit breaker.

Arc Density Versus Temperature

The data also shows that arc density on Vdc is somewhat greater than Vac. The alternating current goes through a zero crossing, which extinguishes the arc, the direct current is a constant power which may account for the difference. No visible distortion was seen in the ac voltage and current time domain waveforms when the arc voltage was less than 40 Vac peak (measured at 100,000 samples per second rate). It appears the current waveform distortion during series arcing comes from the circuit interruption and not from the arcing alone.

Data reduction of the arc voltage was used to determine the arc density. The arc voltage was measured from the line side of the circuit breaker to the lug terminal to ensure the measurement accuracy. There was a 2 Volt drop across the measurement without any vibration. This figures was subtracted from the measurement to determine the arc voltage. Table 3 calculates the arc energy that accounts for the temperature rise over ambient temperature. Figures 5 and 7 show the arc voltage. The arc for both ac and dC tests are of short duration (80-600 microseconds) with an average of 300 microseconds per arc. The voltage ranged from 1-50 volts with an average of 10 volts.

Table 3. Series arc tests calculated average energy.

Arc Density (Arc/sec)	Arc Voltage** (Volts)	Arc Current (Amps)	Arc duration* (Seconds)	Time (Seconds)	Temperature* C	Energy (Watt*sec)
400	10	2.7	0.0003	1	57	3.24
400	10	5	0.0003	1	N/A	6
400	10	6.8	0.0003	1	119	8.16
400	10	8.7	0.0003	1	127	10.44

* Temperature rise over 25°C ambient temperature.

The temperature measurement shows a maximum temperature of 57°C due to approximately 3.2 watts of arcing energy. Similarly, the maximum temperature rose to 119°C for 8.1 watts of arcing energy and 127°C for 10.4 watts of arcing energy.

Terminal Heat Dissipation

A #8 terminal was used for a 25-amp circuit breaker. The terminal must dissipate the energy for a 0.0025-ohm connection. The energy is calculated to be 1.56 watts. The calculated energy for the series arc is two times higher for the 2.7 amps than what the terminal is designed to dissipate. The 6.8-amp test created 5.3 times the heat, and the 8.7 amp test created 6.7 times the normal energy to dissipate. The increased energy accounted for the temperature rise; however, heat transfer and heat dissipation to the air was not accounted for the heat temperature on the lug.

Conclusion

Series arcing on a loose terminal is a complex event with many variables including vibration, wire installation, and carbon build up. Series arc on a loose terminal will raise the temperature on the terminal lug for both ac and dc circuits. The load current above 6.8 amps created enough heat to raise the lug temperature over 100°C. The arc density over 400 arcs per seconds will create the carbon and the necessary heating to cause the temperature rise. Series arc protection should be considered for circuit breakers and load currents above 5 amps. However, detecting series arcs via the time domain voltage current is hard to distinguish from normal voltage and current deviations.